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The Dynamics of the Aurora
VII. Equatorward Motions and the Multiplicity of Auroral Arcs+

by

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ABSTRACT

Equatorward motions of auroras are described in detail as follows:

1. The equatorward shift associated with the earth's rotation;
2. The equatorward motion during the recovery phase of the auroral substorm; and
3. The equatorward spread of irregular bands during the substorm.

The multiplicity of arcs associated with the equatorward motion is also described.

author

1. Introduction

It has been statistically established that the earth rotates once a day under the auroral oval which is, as a first approximation, fixed with respect to the sun [Feldstein, 1963]. The oval is eccentric with respect to the dipole pole, and its center is displaced toward the dark hemisphere along the midnight meridian.

Therefore, the distance between a fixed point on the earth's surface (say, an auroral zone station) and the oval varies systematically during the course of 24 hours; it is longest in the noon sector and shortest in the midnight sector (see Figure 4 of Part V of this series). Thus, the daily rotation of the earth results in an apparent equatorward motion of auroral arcs and bands in the evening sector. In fact, it is well known that at an auroral zone station auroras appear first near the northern horizon (in the Northern Hemisphere) in the early evening and draw gradually closer to the station as the night progresses.

During the early phase of the auroral substorm (the expansive phase), bright auroral bands move rapidly poleward, and this type of motion was the subject in Part V of this series. During the recovery phase of the substorm, however, these bands tend to return toward their initial location, namely equatorward. Since such a motion is a part of the transient process (the auroral substorm), its speed varies greatly.

During the expansive phase of the substorm, auroral bands in the midnight and morning sectors become folded in an extremely irregular manner (see Part VI of this series), and the resulting irregular bands or 'patches' 'spread' equatorward.

Therefore, it is possible to distinguish at least three types of equatorward motions in all-sky films: the equatorward shift associated with the earth's rotation; the equatorward motion during the recovery phase; and the equatorward 'spread' of irregularly folded bands and 'patches'. It is the purpose of this paper to describe in detail these equatorward motions (§ 2, § 3, and § 4).

In general, auroral arcs and bands are multiple. It is quite common to observe a few arcs stretching across the field of view of a single station. The multiplicity is most clearly seen when auroras are moving equatorward. In § 5, this multiplicity is described in some detail.

2. Evening Equatorward Shift Associated with the Earth's Rotation

The center line of the auroral oval lies, on the average, at about dipole latitudes (dp lat) 72° ~ 73° in the early evening sector (19-21 LT (= local time)). Thus, when we observe this narrow belt in a particular sector, say in the Alaskan sector, it descends gradually from a little north of the Arctic coast to the latitude of the auroral zone (dp lat 67°) or less in the late evening sector (21-24 LT).

While this is statistically true, the shift varies greatly from one day to another. The crossing time of the center line of the auroral oval at a particular station differs from one day to another. Further, on some days, the oval descends slowly as we expect from a simple consideration that the oval shifts from dp lat 72° to 65° in about 4 ~ 5 hours, namely with a speed of 40 ~ 50 m/sec; however, on some other days, it descends much faster than the above speed.

We infer that such a difference is partly due to the fact that the pattern of the auroral oval is not necessarily fixed in space, but deforms itself in a complicated manner. The 'diameter' and the eccentricity of the oval differ from one day to another [Akasofu, 1964a]. A sudden increase of the 'diameter' of the oval often occurs when the auroral substorm occurs after a relatively quiet period [Stringer, Belon, and Akasofu, 1965]. However, in general, in the midnight and the late evening sectors, this is masked by the poleward expansion of the width of the oval; in the early EVENING ~~morning~~ sector (or even in the late evening sector when the substorm is weak) the most common effect of the substorm on individual arcs is to increase their brightness [Akasofu, 1965]; thus, the expansion is most clearly seen there. In the late morning sector, we see also the equatorward motion until arcs begin to disintegrate [Akasofu, 1964b]. Therefore, the earth rotates under the continuously changing oval. The minimum latitude attained by the oval in the midnight sector also depends on the intensity of the main phase decrease [Akasofu and Chapman, 1963].

Further, when this particular phenomenon is examined 'microscopically', it appears to be the shift of a narrow region in which auroral arcs and bands evolve continually. Some become bright and some fade, and there is a continuous change of the distribution of arcs and bands in the narrow region. Therefore, it is, in general, not possible to follow the equatorward motion of a particular arc or band for more than one hour, unless it is very bright and stands out from others quite distinctly (although there is a possibility that the present all-sky camera system does not have enough time and spatial resolutions to follow such a motion, and in this respect it is highly desirable to examine the growth and decay or the lifetime of individual arcs by a high resolution camera, such as that developed by Davis and Hicks [1964]).

Figure 1a shows the locations of a group of auroral arcs and bands over Fort Yukon (dp lat 66.7° N) and College (dp lat 64.7° N) during the evening hours of February 22, 1958 (150° WMT); the locations are given in terms of the distance from the Fort Yukon zenith. The northern and southern envelopes of this whole auroral system define the northern and southern boundaries of the auroral oval, respectively. Between the two envelopes, a number of arcs and bands continually evolve, but only a few of them are identified for a reasonably long period to determine their equatorward speed. The equatorward speeds of the arcs marked by A, B, C, and D are, respectively, 100 m/sec, (75-230) m/sec, 190 m/sec, and 140 m/sec.

Figure 1b shows the locations of auroral arcs and bands over the Arlis ice floe III (dp lat 71° N) in the evening of March 4, 1964 (150° WMT). Being at a higher dp latitude, the oval crosses the zenith about 2 hours earlier than at Fort Yukon; during the entire period of observation (about 2 months) this was a common feature in the evening [Hessler, 1965]. Again, it should be noted that although the equatorward shift of the whole auroral system is quite clear, the identification of individual arcs is rather difficult, particularly in such a high latitude, because auroras are fainter and more variable there than those in lower latitudes.

3. Equatorward Motion during the Recovery Phase

Figure 2 shows an example of the equatorward motion during the recovery phase of an auroral substorm which began at about 2350, 165° WMT on February 18, 1958, at Kotzebue, Alaska (dp lat 63.7° N). The average speed of the motion was bout 240 m/sec. The equatorward motion was disrupted at 0122, 165° WMT, when a new substorm began and bright bands moved rapidly poleward. Such a north-south motion repeatedly takes place when the auroral substorms occur successively during geomagnetic storms [cf. Akasofu, 1962; Akasofu and Chapman, 1963; Akasofu, 1965]. It should be noted in Figure 2 that auroral bands tend to lie in the east-west direction, rather than the north-south direction, during the motion, so that the north-south motion can be well expressed by the expansion and subsequent contraction of the width of the oval.

The speed of the equatorward motion associated with the substorm varies greatly. On some occasions, a speed of as high as 800 m/sec or more can occur, but the most common speeds are of order 100-250 m/sec. It is interesting to compare these speeds with those of the most common poleward expansive motion, 500 ~ 600 m/sec (see Part V of this series). Therefore, the recovery phase proceeds much more slowly than the expansive phase.

The speed of the equatorward motion of individual auroral arcs and bands has been obtained for 77 cases and is shown in the following table:

Speed (m/sec)	No. of Cases
0 - 50	2
50 - 100	6
100 - 150	14
150 - 250	15
200 - 250	16
250 - 300	5
300 - 350	7
350 - 400	4
400 - 500	4
500 - 600	0
600 - 700	1
700 - 800	0
800 - 900	2
900 - 1000	0
1000 <	

4. Equatorward Motion of Irregular Bands during the Substorm

During an auroral substorm, the equatorward boundary of the auroral oval also expands equatorward. Unlike the poleward motion of bright auroral bands, however, this equatorward motion is not due to their systematic motion. Rather, extremely irregular bands or patches 'spread' equatorward. Figure 3a shows the successive projection of auroras during an intense substorm which began at about 2331 (150° WMT) on December 25, 1957 over the central Alaskan sky. An arc stretching midway between College (dp lat 64.7° N) and Farewell (dp lat 61.4° N) became brighter from its eastern part and developed a multiple structure at 2334. Then, they began to move rapidly poleward with a speed of about 1070 m/sec, which is a typical feature of the expansive phase of the substorm.

At the same time, irregular bands appeared between College and Farewell and began to spread in the SW direction. Their motions are too irregular to obtain the speed. In general, the extent of this equatorward motion is less than that of the poleward motion.

5. Multiplicity of Auroral Arcs

The multiple arcs are most clearly seen during the equatorward motions of the aurora. This is due to the fact that equatorward moving arcs tend to be less active than poleward moving arcs. Activated bands tend to develop folds of various scale-lengths which makes it difficult to define the distance between two such bands (see Part I of this series). Further, the multiplicity is more common in the evening sector than in the morning sector, since auroras in the morning sector tend to develop irregular folds during even a very weak substorm (see Part VI of this series).

Figures 1a and 1b show an example of the distribution of multiple arcs in the oval. At present, it is rather difficult to state a reliable statistical result for the most frequent number of multiple arcs over the entire Alaskan sky, although it is common to observe several arcs stretching across the sky. In Figure 1a, eight arcs were seen at times in the combined field of view of Fort Yukon and College.

The most common separation distance between two arcs seen at single stations is between 30 and 40 km, and there are some arcs separated by more than 100 km. Figure 3 shows the histogram of the occurrence frequency of different separation distances between two arcs; it is obtained by combining individual all-sky ground projections from Alaskan stations.

There is no doubt that such a multiple structure of auroral arcs is an important clue to understand the mechanism by which auroral particles are accelerated in the tail region of the magnetosphere. In other words, the mechanism tends to be multiple in nature, rather than singular, and their spatial structure in the magnetospheric tail must be such as to produce several arcs, with the most common separation distance of order $30 \sim 40$ km.

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FIGURE CAPTIONS

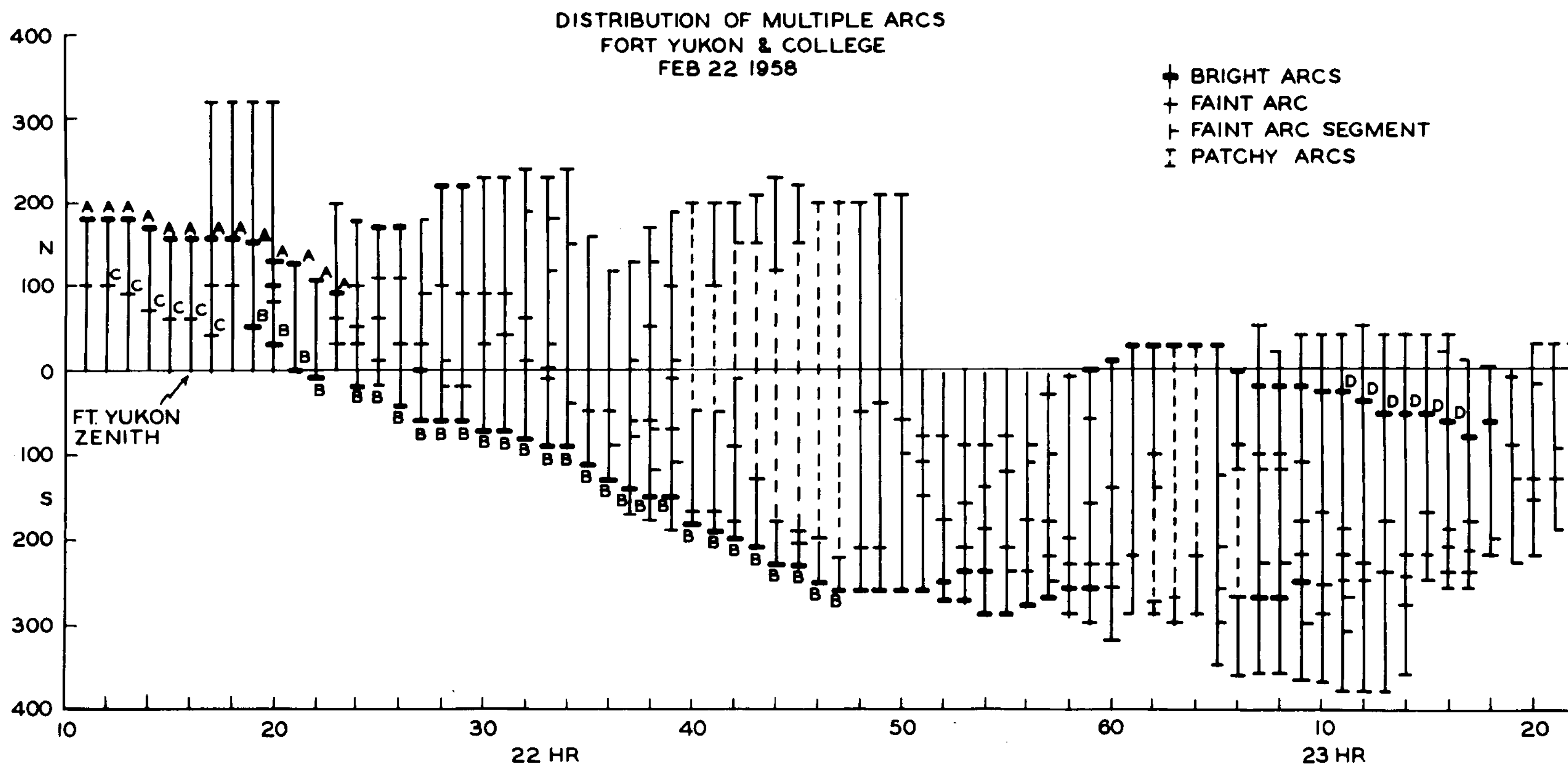
Figure 1a. Equatorward shift of the auroral oval over Central Alaska in the evening of February 22, 1958 and the distribution of arcs in the oval; the locations of the arcs are given in terms of the Fort Yukon zenith distance.

Figure 1b. Equatorward shift of the auroral oval over the Arlis III ice floe (dp lat 71° N) in the evening of March 4, 1964.

Figure 2. Ground projection: Equatorward moving multiple arcs (0058-0121, 165° WMT, February 18, 1958) and the poleward motion (0122 on) caused by a new substorm; Kotzebue (dp lat 63.7° N), Alaska.

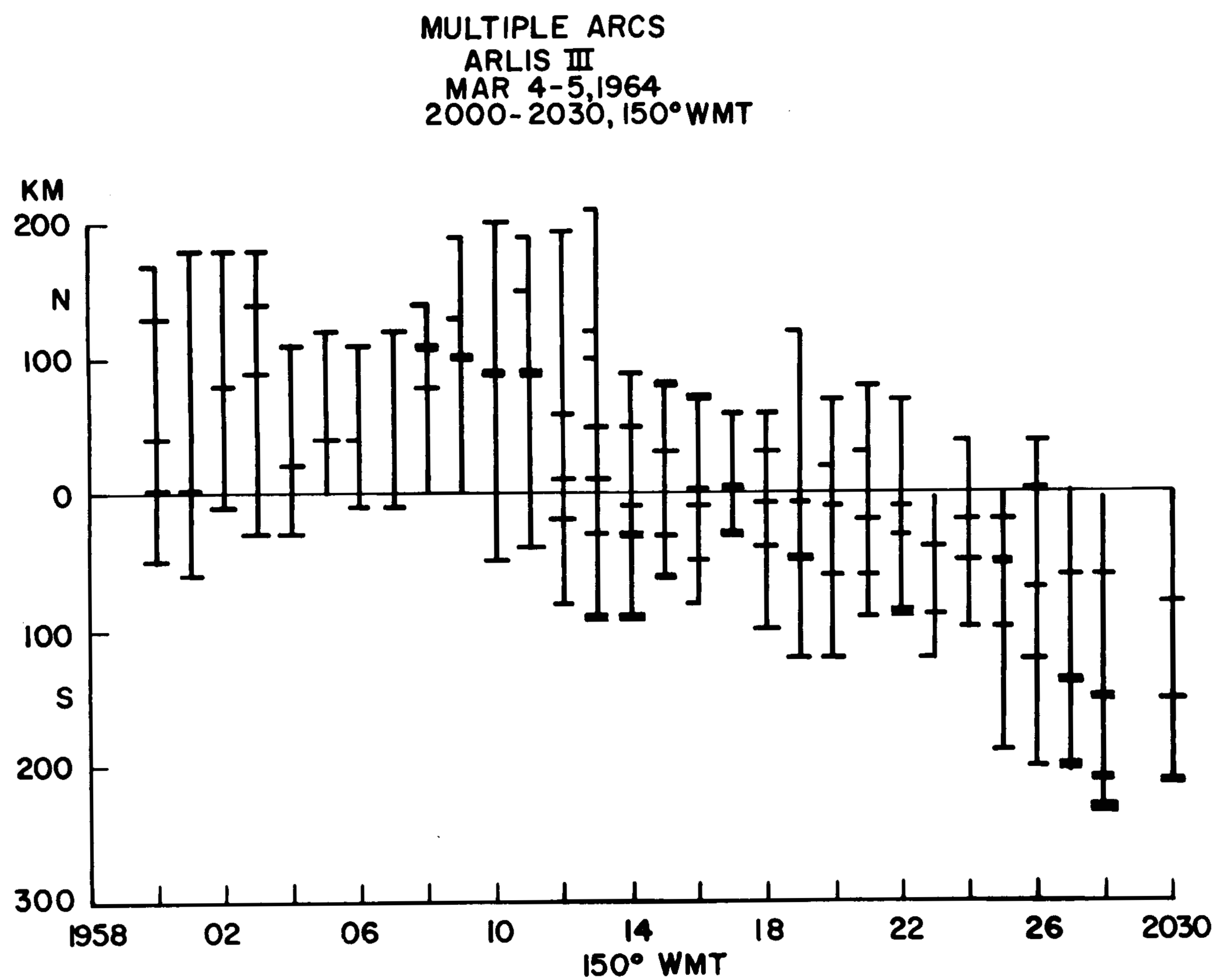
Figure 3. Distribution of auroras over Central Alaska during an intense auroral substorm on December 25, 1957. Note a violent poleward motion of bright bands and a complicated equatorward motion of irregular bands.

Figure 4. Histogram to show the occurrence frequency of various separation distances of auroral arcs (observed at single stations in Alaska).



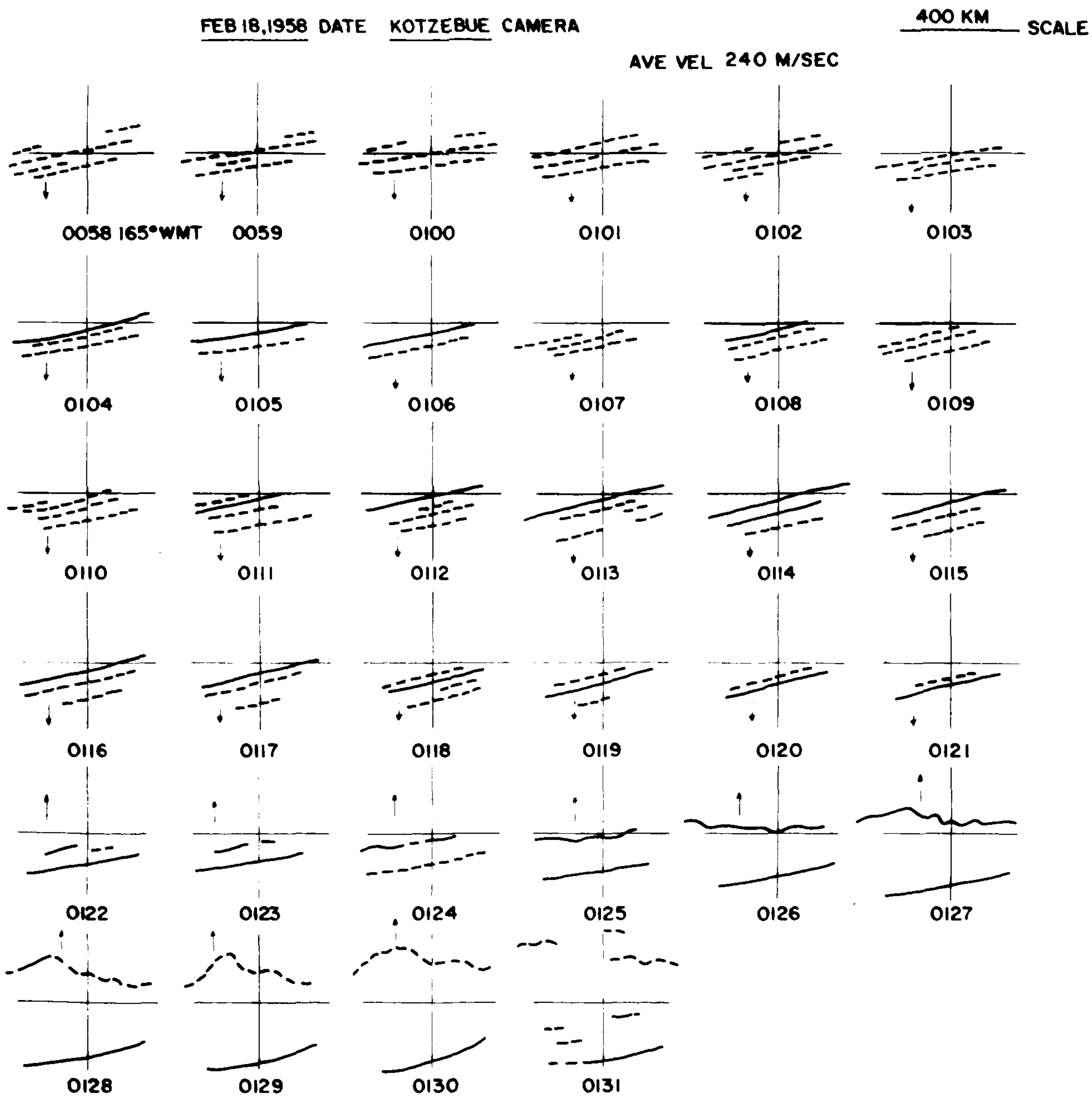
DISTRIBUTION OF MULTIPLE ARCS
FORT YUKON & COLLEGE
FEB 22 1958
BRIGHT ARCS
FAINT ARC
FAINT ARC SEGMENT
PATCHY ARCS
FT. YUKON ZENITH
N
S
22 HR
23 HR

Figure 1a



MULTIPLE ARCS
ARLIS III
MAR 4-5, 1964
2000-2030, 150° WMT
KM
200
N
100
0
100
S
200
300
1958
02
06
10
14
18
22
26
2030
150° WMT

Figure 1b



FEB 18,1958 DATE
KOTZEBUE CAMERA
400 KM SCALE
AVE VEL 240 M/SEC
0058 165°WMT
0059
0100
0101
0102
0103
0104
0105
0106
0107
0108
0109
0110
0111
0112
0113
0114
0115
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0125
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0129
0130
0131

Figure 2

COLLEGE-FAREWELL DEC 25 1957

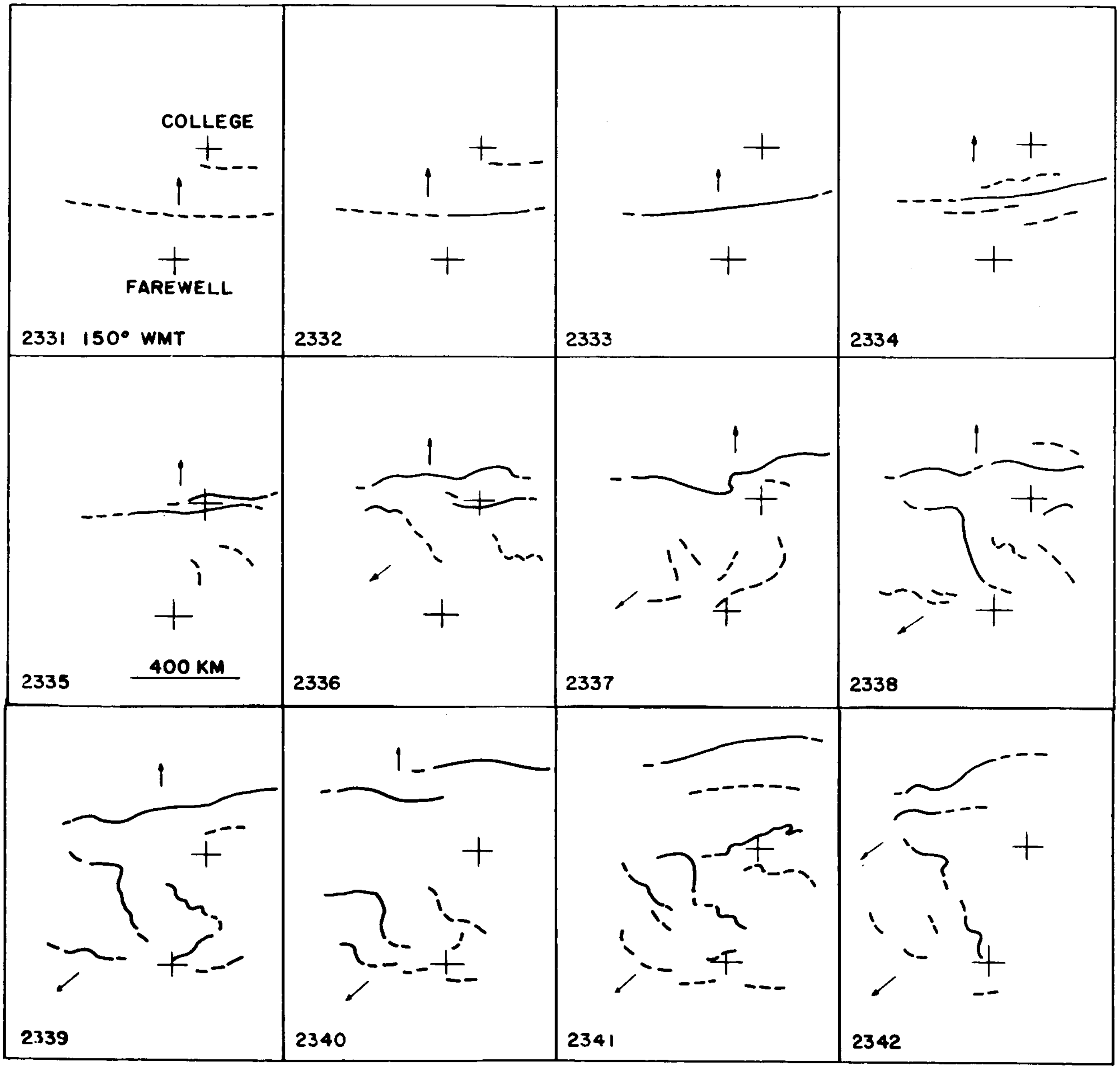
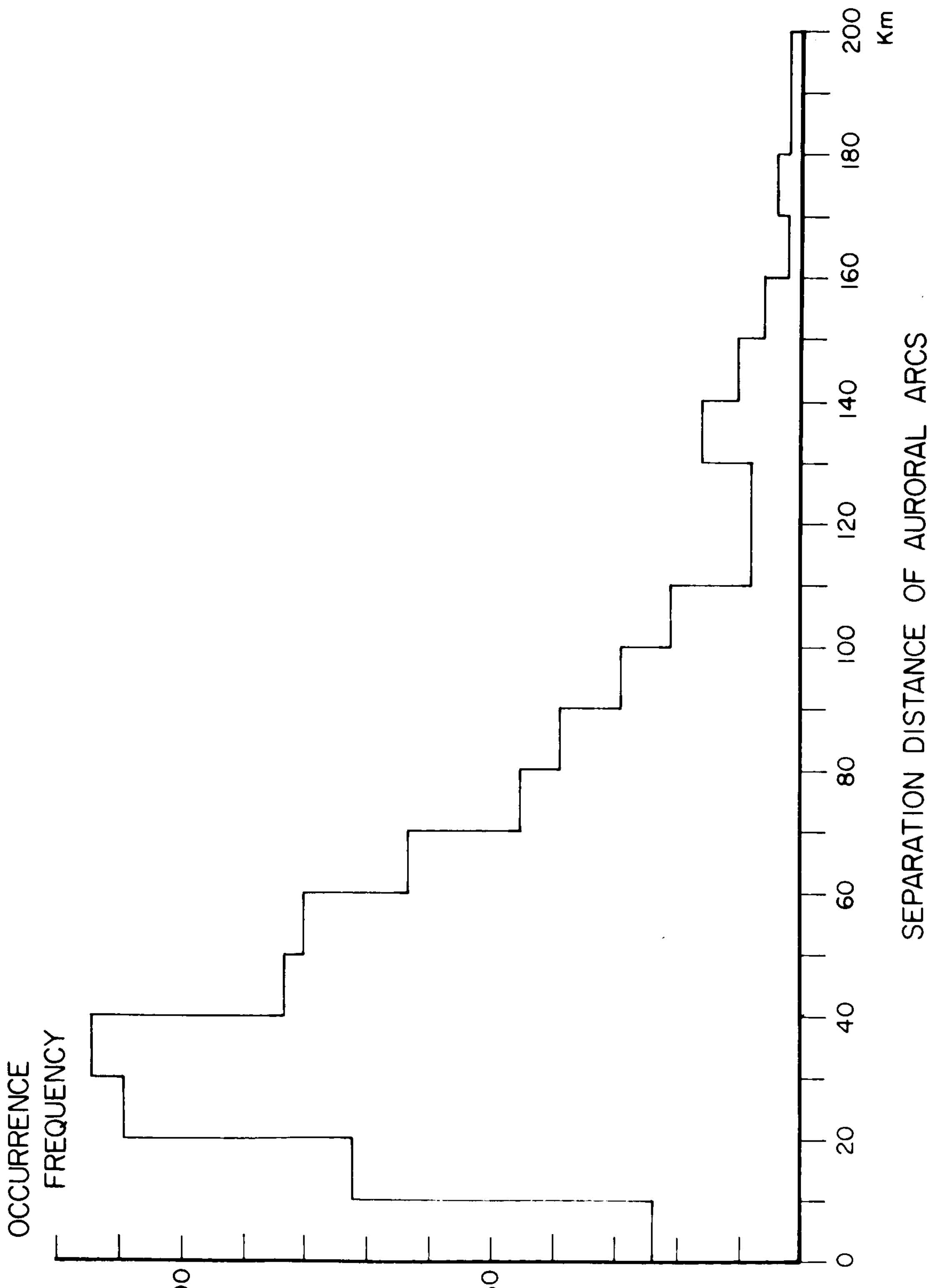


Figure 3



OCCURRENCE
FREQUENCY
100
50
0
20
40
60
80
100
120
140
160
180
200
Km
SEPARATION DISTANCE OF AURORAL ARCS

Figure 4